DIRECT OBSERVATION OF POLARONS AND PHONONS DURING TUNNELING IN GROUP 3-5 SEMICONDUCTOR JUNCTIONS

R. N. Hall, J. H. Racette, and H. Ehrenreich
General Electric Research Laboratory, Schenectady, New York
(Received April 6, 1960)

Narrow p-n junctions in which most of the conduction for small applied voltages results from tunneling have been studied in the 3-5 compounds InSb, InAs, InP, GaSb, GaAs, and GaP. With the exception of GaP, all of these compounds are believed to have both conduction and valence band edges located at the center of the Brillouin zone. Thus, the tunneling of an electron from the bottom of the conduction band to the top of the valence band does not necessitate a large change of wave vector as in Ge and Si tunnel diodes[1] and the observed structure in the electrical characteristics produced by the assisting phonons is absent. Instead, the low-temperature electrical characteristics of group 3-5 junctions show structure of an entirely different kind which is clearly related to the polar character of these semiconductors and whose magnitude correlates with the polar electron-phonon coupling constant[2] $\alpha = (e^2/\hbar)(m^*/2\hbar\omega_l)^{1/2}(\epsilon_\infty^{-1} - \epsilon_0^{-1})$. Threshold voltages are observed corresponding to the energy $\hbar\omega_l$ necessary for the creation of a long-wavelength longitudinal optical phonon. A pronounced conductance minimum, which appears near zero bias, is attributed to a threshold at the energy required to move an electron adiabatically from a polarized electron state to a polarized hole state.

The junctions were prepared by fusing mixtures of suitable alloys to degenerately doped n- or p-type semiconductor wafers. The alloys which were used consisted of elements from the second, fourth, or sixth columns of the periodic table and sometimes contained further additions of the Column 3 constituent of the wafer, i.e., Ga or In.

The electrical characteristics were observed by cooling the diodes to 4.2°K by immersion in liquid helium and plotting the current-voltage characteristic using an X-Y recorder. While the structure to be described can be seen by careful inspection of the current-voltage characteristic itself, it is more clearly revealed by a circuit (suggested by J. J. Tiemann) which causes the recorder to plot the conductance (dI/dV) as a function of the voltage, V. Photographs of several representative recordings of this kind are shown in Fig. 1. The data which we report were

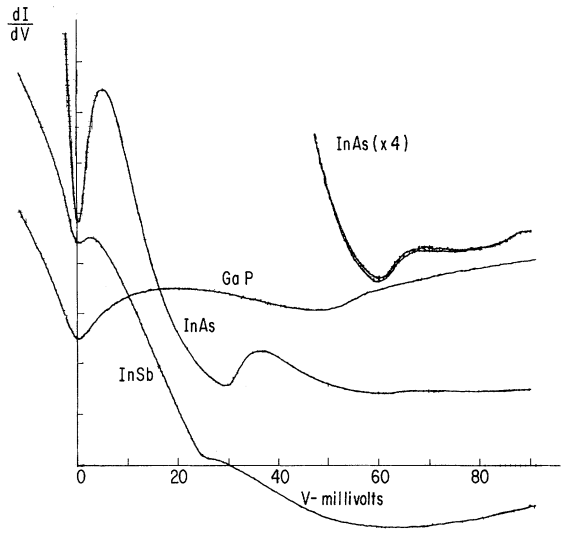

FIG. 1. Conductance (dI/dV) in arbitrary units vs voltage for several group 3-5 junctions.

obtained from measurements of at least four junctions in each of the materials studied, with the exception of InP where only one junction was examined.

The conductance curves exhibit distinct minima in the neighborhood of zero voltage. These minima are invariably observed in these polar semiconductors and they tend to be more pronounced in compounds having a larger electron-phonon interaction. We interpret the reduced transition probability near zero bias as arising from the lowering of the electron and hole energies due to self-interaction with the phonon field (polaron formation). In tunneling processes that occur rapidly compared to the lattice relaxation time and at sufficiently low temperatures that the Fermi distribution characterizing the electrons is sharp, the applied voltage must supply the relaxation energy necessary to move the electron rapidly between differently polarized regions of the crystal. It can be shown by consideration of the energy cycle for the process that this relaxation energy is $\frac{1}{2}(\alpha_c + \alpha_v)\hbar\omega_l \approx \alpha_c\hbar\omega_l$, where α_c and α_v are the coupling constants for the conduction and valence bands, respectively. The thresh-

Table I. (Energies in ev $\times 10^{-3}$.)

	Deduced from other expts.			Present expts.	
	α_c	$\hbar\omega_l$	$\alpha_c\hbar\omega_l$	$\alpha_c\hbar\omega_l$	V_t
InSb	0.02	22.8	0.4	0.4 ± 0.1	24
InAs	0.05	28.8	1	1 ± 0.5	30.5
InP	0.08	42.0	4	4	45
GaSb	0.02	29.0	0.6	0.5 ± 0.2	29.6
GaAs	0.06	35.2	2	0.1 ± 0.05	36
GaP	0.1	49.9	6	6 ± 3	52

old voltages for this process are not clearly resolved in Fig. 1 because of temperature broadening which, at 4.2°K, is sufficient to obliterate much of the detail which this model suggests.

The rough comparison, shown in Table I, of the threshold estimated from the magnitude of the minimum in the experimental curves with the self-energy calculated from independent experimental data (but not corrected for screening[3]) lends credence to the present hypothesis. The agreement between observed and calculated values is reasonable, except in the case of the GaAs junctions, which were narrower and much more heavily doped than the others.

The possibility that the conductance minimum is associated with the creation of low-energy acoustical phonons can be ruled out by the absence of a corresponding temperature dependence of the tunneling current. The fact that the valence band edges are not at $k = 0$ but slightly displaced[4] is also unable to account for this effect, since estimates show that it is too small, and in addition the correlation with the spin-orbit splitting to be expected under these conditions is absent.

It is seen from Fig. 1 that the slope of the conductance curve again changes abruptly at a higher voltage V_t. We interpret this phenomenon as the threshold for a new process which is characteristic of the host crystal and demonstrably independent of the concentration or chemical nature of the impurities used to produce the junction. It represents the onset of tunneling processes in which a longitudinal optical phonon is emitted simultaneously with the passage of an electron through the junction. As shown in Table I, the observed threshold voltages agree within experimental error with the sum of the polaron relaxation energy and that of the zone-center longitudinal optical phonon as calculated from optical reflectivity data.[5,6] Since these processes depend upon the coupling of the electron to the lattice, their probability may be expected to be proportional to α. This expectation is qualitatively confirmed by the observation that the structure is more pronounced in the more polar compounds, InAs, InP, and GaP, and is relatively weak in junctions made from InSb, GaSb, and GaAs, where the coupling constant is smaller.

The conductance curve for InAs, shown in Fig. 1, exhibits an additional contribution to the tunneling current beyond a voltage which is equal to $(2+\alpha_c)\hbar\omega_l$ within the accuracy of these experiments. This component, which presumably corresponds to the tunneling of an electron accompanied by two optical phonons, is frequently observed in the characteristics of the more polar 3-5 compounds, with an amplitude that is smaller than that of the one-phonon process by a factor of 5 or 10.

The fact that structure corresponding to that just discussed is totally absent in Ge and Si is due to the considerably weaker electron-phonon coupling in these materials as contrasted to the rather strong interaction in the group 3-5 semiconductors arising specifically from their polar character.[3]

The type of measurement discussed here permits a direct experimental determination of the polar electron-phonon coupling constant. Furthermore, these results imply that the tunneling process takes place in a time short compared with the lattice relaxation time.

We are grateful to N. Holonyak for supplying some of the InP and GaP junctions, and to H. Haken and H. Brooks for helpful discussions.

---

[1]H. Holonyak, Jr., I. A. Lesk, R. N. Hall, J. J. Tiemann, and H. Ehrenreich, Phys. Rev. Letters 3, 167 (1959).

[2]H. Fröhlich, Advances in Physics, edited by N. F. Mott (Taylor and Francis, Ltd., London, 1954), Vol. 3, p. 325.
[3]H. Ehrenreich, J. Phys. Chem. Solids 2, 131 (1957); 8, 130 (1959).
[4]E. O. Kane, J. Phys. Chem. Solids 1, 245 (1957).
[5]G. Picus, F. Burstein, B. W. Henvis, and M. Hass, J. Phys. Chem. Solids 8, 282 (1959).
[6]D. Kleinman and W. Spitzer, Phys. Rev. 118, 110 (1960).

NUCLEAR SPIN RELAXATION IN SOLID He^3†

J. M. Goodkind* and William M. Fairbank*
Duke University, Durham, North Carolina
(Received April 5, 1960)

The liquid states of both helium isotopes have been of particular interest due to their peculiar macroscopic properties which have been attributed to quantum effects. In solid He^3 the nuclear susceptibility departs from Curie's law,[1-3] below 0.2°K, indicating that some exchange interaction must be present in addition to the direct dipole-dipole interaction between atoms. Thus solid He^3 is also found to exhibit some such peculiar properties. A further distinctive property of solid He^3 is the α-β phase transition discovered by Grilly and Mills.[4] This transition has no analog in solid He^4, and its nature is not yet understood. Some relevant information contained in the original work of Grilly and Mills is that the volume change associated with the transition approaches zero at approximately 2°K. In the work to be described here, nuclear spin relaxation times were measured in solid He^3 such that they might yield additional information as to these properties.

Free-precession techniques were used to measure both the transverse and longitudinal relaxation times at 30.4 Mc/sec to an accuracy of roughly 10%. The measurements were made both as a function of pressure at constant temperature and as a function of temperature at constant volume. In order to allow pressure variation of the sample, a loop of resistance wire was placed inside of the capillary through which the He^3 entered the sample chamber. In this way, by passing a current pulse through the wire, the plug of solid He^3 which formed in the capillary could be melted momentarily and the solid in the sample chamber could come to pressure equilibrium with the vapor in the warmer part of the capillary.

Large discontinuities in both relaxation times were observed as the pressure was increased or decreased across the α-β phase boundary above approximately 2°K. Figure 1 shows the data at

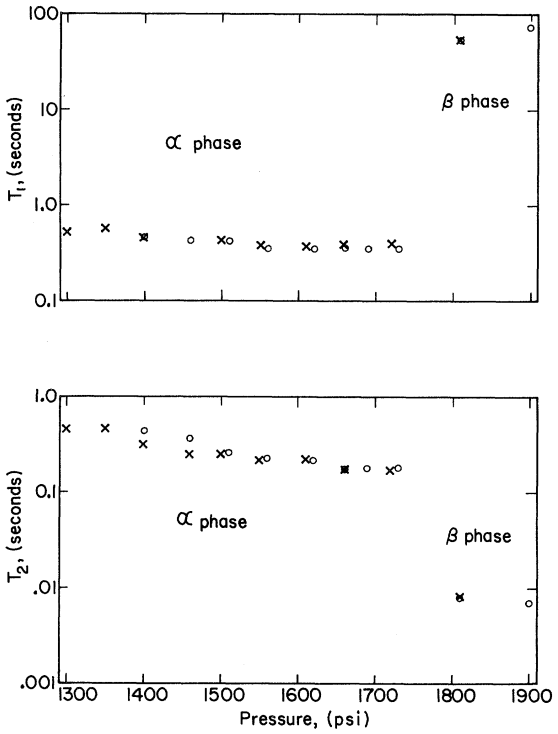

FIG. 1. Nuclear spin relaxation times in solid He^3 as a function of pressure at 2.2°K, indicating a discontinuity at the α-β phase boundary, discovered by Grilly and Mills (reference 4). Circles and crosses represent, respectively, data taken while increasing and decreasing the pressure.

2.2°K. The circles represent the data taken while increasing the pressure in steps and the crosses those taken while decreasing the pressure. At 1.37°K, however, the relaxation times displayed an exponential dependence on the pressure in the α phase and no discontinuity at the phase boundary. This may be seen in Fig. 2, where it may also be seen that T_1 passes through a minimum